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PATENT

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First Named Inventor	: Stefan HELGEE, *et al.*		
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Customer No.	: 23911		
Title	: Method For Arc Welding of Ductile Cast Iron		

DECLARATION UNDER 37 C.F.R. §1.132

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Sir:

I, Jorma Tani, declare that:

1. I am a resident and citizen of Sweden. I and Stefan Helgee are co-inventors of the invention described in the above-identified application.

2. I have 35 years of experience in the field of arc welding, and in particular have been involved in both welding training and education and in optimization of welding processes for our customers. I have worked with a variety of materials, and especially with arc welding of mild steel, stainless steel, aluminum and cast iron.

3. I am currently a Specialist in welding and cutting, engineer in The Linde Group, one of the world's largest suppliers of industrial gases, specialty gases and

developers of welding processes. Before working for The Linde Group, I was employee of AGA AB, and I continue to work with AGA Gas AB within the Nordic Region.

4. In the prior art, the main trouble in arc welding cast iron as known before my invention was the high sensitivity to crack formation due to carbon precipitation that forms martensite or other brittle metallurgical phases. To avoid crack formation, only a low weld bead deposition rate was used in the prior art, resulting in a low productivity in customer production environments. So the problem to be solved was to allow welding of cast iron with a high productivity.

5. In welding of ferritic materials, you have to differentiate between carbon steel, stainless steel and cast iron, which have markedly different reactions to process parameters such as heat input, shield gas interaction, and cooling rate effects on microstructure. Especially the attributes of cast iron differ from carbon and stainless steels, because cast iron has a carbon content about 3.5 % whereas carbon steel and stainless steel has a carbon content of circa 0.15 %, and most of the carbon content in ductile cast iron is in the form of spherical graphite nodules, but finely distributed carbon. When ductile cast iron is heated in the welding process, the graphite nodules will start to dissolve, with the highly undesirable result that the carbon precipitates to the surrounding iron and forms brittle structures like martensite. This difficult-to-control carbon behavior is the reason why cast iron has historically been very difficult to weld, and the reason production-scale use of cast

iron welding has been very limited (*i.e.*, production limited by the need to limit weld bead deposition rates to low speeds and low energy deposition in order to minimize carbon precipitation).

6. The invention in this application is the use of a shielding gas which with 1 to 25 Vol-% carbon dioxide and/or 0.5 to 10 Vol-% oxygen in argon or in an argon-helium-mixture makes a welding of ductile cast iron possible, something my experience in the field for 35 years allows me to say was not previously believed to be possible at high commercial-production-level weld deposition rates. By this shield gas application, even a welding of ductile cast iron to steel is possible.

7. An example of the unexpected results obtained with the use of the above-identified shielding gas mixture is shown in the enclosed comparison of the microstructures in the interface between ductile cast iron and weld. In this comparison, using an embodiment of the claimed mixture (*i.e.*, argon and 8 Vol-% carbon dioxide) the weld result is good, in that any significant excess carbon precipitation is avoided. In contrast, when using a shielding gas mixture out of the claimed region (here, argon and 25 % carbon dioxide), the weld result is, as would be expected based on conventional knowledge in the welding arts, unacceptable, with a build-up of highly undesirable martensite (*e.g.*, the martensite formation is at the border of the ductile cast iron (left side in the second figure) and the weld (right side).

8. The unexpected nature of the results of our development is reflected in the recognition of the invention by our peers. For example, in response to our submission and presentation of a technical paper before one of the principle technical societies in the field, the American Foundry Society, the Society presented an award to Linde Gas (documented by the enclosed November 21, 2006 letter), noting that "[t]he technology described in this paper significantly improves the properties of the heat affected zone when welding ductile iron castings to steel. This technology will allow ductile iron foundries and design engineers to develop new components that combine the versatility of casting with weldments and fabrications." The Society's awards are only given out once every four years, and I believe that being selected for the award demonstrates the relevance and the importance of this invention, and its non-obviousness to our peers in the art.

I declare that the preceding statements which are made from my own knowledge are true and that the preceding statements which are made on information and belief are believed to be true.

I am aware that willful false statements and the like are punishable by fine or imprisonment or both under Section 1001 of Title 18 of the United States Code and may jeopardize the validity of the application or any patent issuing thereon.

Jorma Tani

February 14, 2008 Jorma Tani

U.S. Patent Application 10/539,773

Declaration

Jorma Tani , Specialist in welding and cutting, engineer in The Linde Group.

I am working in arc welding for years. Before working for The Linde Group I was employee of AGA AB and now today I am working in AGA Gas AB within the Nordic Region. My basic qualifications are schooling, training, education and optimization of welding processes at our customers.

Therefore, I have 35 years of experience in arc welding. During this time I worked with all usual metallic materials. Especially I work on arc welding of stainless steel, aluminum and cast iron.

The main trouble in arc welding cast iron as known before my invention was the high sensibility to crack formation due to carbon precipitation that forms martensite or other brittle metallurgical phases. To avoid crack formation only a low deposition rate was used and those causes to a low productivity. So the problem to be solved was to allow welding of cast iron with a high productivity.

In welding of ferritic materials you have to differ between carbon steel, stainless steel and cast iron. Especially the attributes of cast iron differ, because cast iron has a carbon content about 3.5 % whereas carbon steel and stainless steel has a carbon content of circa 0.15 %. The most of the carbon content in ductile cast iron is in the form of spherical graphite nodules. When the ductile iron is heated because of the welding process the graphite nodules will start to dissolve and carbon is precipated to the surroundings and form brittle structures like martensite This is the reason why cast iron is very difficult to weld.

My invention is that to use a shielding gas with 1 to 25 Vol.-% carbon dioxide and/or 0.5 to 10 Vol.-% oxygen in argon or in an argon-helium-mixture makes a welding of ductile cast iron possible. Even a welding of ductile cast iron to steel is possible. Only if such a shielding gas is used the welding process can be controlled adequately and the productivity is satisfactiorily.

To show the differences in welding with a shielding gas mixture as claimed and a shielding gas mixture not claimed I enclosed a comparison of the micro structures in the interface between ductile cast iron and weld. In the case of using a claimed mixture (i.e. argon and 8 Vol.-% carbon dioxide) the weld result is good and in the case using a shielding gas mixture out of the claimed region (i.e. argon and 25 % carbon dioxide) the weld result is bad and a building of an unwished martensite is shown.

The marternsite formation is built at the border ductile cast iron (see at the left side in the second figure) and the weld (see at the right side).

My invention is prestigious among experts. So the American Foundry Society awarded Linde Gas for a presentation of the welding method of this invention with the motivation that this method leads to an import progress in the use of ductile iron. The award is only done every fourth year, so the election shows the relevance and the importance of my invention. Enclosed are the price motivation and the conference paper.

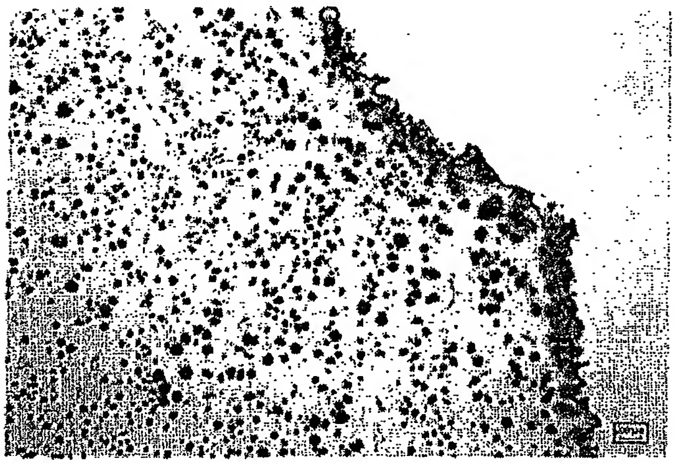
For welding ductile cast iron while fulfilling demands on quality and productivity my intention is essentially. To use a gas mixture as claimed is not obvious; it is my invention.

didingö 3.12.2007
place/date

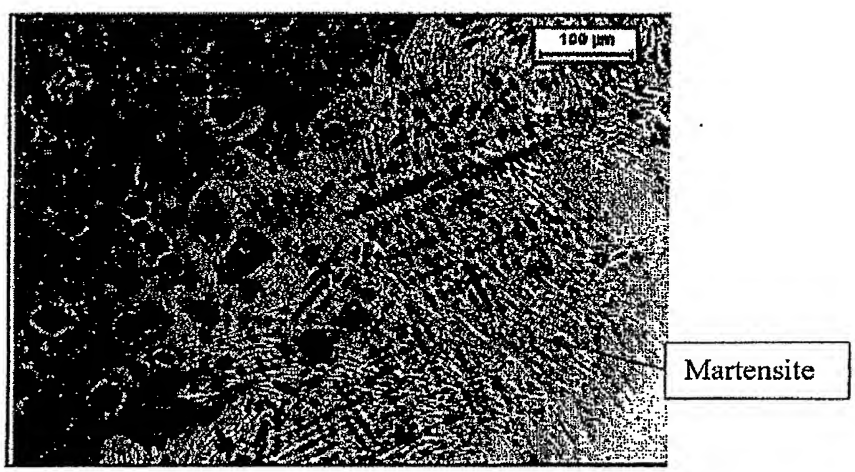
Jorma Tami
< name of inventor >

Encls.
-Comparsion of welds
-Invitation of the American Foundry Society
-Conference paper

Micro structures in the interface between ductile iron and weld showing a good weld result and a bad weld result



Good weld
Shielding gas: Ar + 8% CO_2



Bad weld (brittle structure in the interface weld – base metal)
Shielding gas: Ar + 25% CO_2

Welding Ductile Iron to Steel : A Reality

M. Gagné and S. Leclerc
Rio Tinto Iron & Titanium Inc., Montréal, Canada

S. Helgee, N. Stenbacka and J. Tani
Linde Gas, Stockholm, Sweden

ABSTRACT

Although the complex shapes produced by the casting processes of today have enabled castings to replace many fabrications, there are numerous applications where castings themselves become parts of a fabrication. In many cases, this may imply joining different parts by welding Ductile Iron components to steel. However, such practices have found limited applications. When welded, Ductile Iron is liquified in the welded area and solidifies with a carbidic structure in the fusion zone that limits the toughness of the weldment. Avoiding the formation of this carbidic zone is a difficult task. Therefore, the target when developing procedures to weld Ductile Iron to steel should be to reduce the detrimental effect of this zone by minimizing its extent.

This paper presents the results of a study whose objective was to improve the mechanical properties of gas metal arc welded Ductile Iron – steel components in order to enlarge the range of applications of such fabrications. Another requirement was that the production rate should be high enough to catch an interest from the heavy vehicle industry. In order to achieve optimum results, it is necessary to use a shielding gas containing both argon and helium in combination with small amounts of some oxidizing components. As will be seen, significant improvements in properties are reported for ferritic and pearlitic Ductile Iron — mild steel welded assemblies. The welding procedures developed were also used for repair welding of Ductile Iron castings and an example is included in this paper.

INTRODUCTION

The history of metal joining can be traced to year 3000 B.C., but its development really accelerated in the late nineteenth century. The discovery by Bernados of a process in which an electric arc is used to melt the edges of two pieces of metal and thereby to join them together [1] allowed the rapid growth of arc welding. It was recognized that such a process could be applied to irons and steels, and since then, the arc welding process has evolved to become the prevalent welding technique for ferrous alloys.

While welding of steels has been rapidly and successfully introduced in all industrial sectors, the difficulty to weld cast irons was recognized very early. Because of its high carbon content, cast iron, liquified during welding, tends to solidify with a carbidic structure limiting the ductility and toughness of the weld. This has restricted the use of cast iron parts in many fabrications that could have taken advantage of the casting process and of its properties. For example, Ductile Irons with properties competing with those of steels would find many new applications if it could be welded without the embrittlement effect. Processes for welding Ductile Irons have been developed [2, 3, 4, 5, 6] but improving the quality of the welds would enlarge the range of applications for Ductile Iron.

This paper presents the results of a R&D program whose objective was to optimize the arc welding process for joining Ductile Iron (ferritic or pearlitic) to steel. Initially targeting a heavy vehicle application, this development was applied successfully to a variety of geometries and uses. The results are presented below.

WELDING PROCESS DEVELOPMENT

PROCEDURES

A requirement set at the starting point of this project was to develop welding procedures that would use existing equipment and be easily introduced in industrial manufacturing processes, i.e. with an acceptable level of productivity. As seen in Table 1, all laboratory and application welding tests were performed with industrial equipment and commercially available consumables. A multi-pass approach was selected to minimize the interactions between the base materials and the heat involved during the welding process.

Table 1. Welding Equipment, Parameters and Consumables

Welding equipment	ESAB Auto 500
Welding operation	Mechanized
Deposition rates	Root pass: 7.7 kg/h, multi pass: 8.6 kg/h
Shielding gas	Linde Gas MISON 2 He (30% He, 2% CO_2, 0.03 NO in Ar)
Filler material	Ni-rod metal 44 (INCO International Alloys)
Wire diameter	1.2 mm

The welding procedures included pre– and post-welding heat treatments which are described in Table 2. In order to identify the heat treatment parameters, test plates were instrumented with thermocouples (Figure 1) to monitor the temperature profiles obtained as a function of the welding parameters studied. Figure 2 presents an example of a typical cooling curve. Heat treatments were either made with a flame or in a furnace.

Table 2. Heat Treatment Parameters

Pre-heating	300 – 320°C
Inter-pass temperature	250 – 300°C
Post-heat treatment	Air cooling, heating to 600 – 620°C and maintain for 2 hours

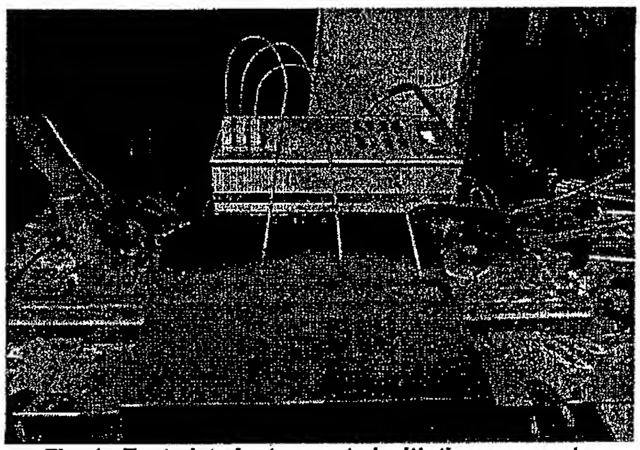


Fig. 1. Test plate instrumented with thermocouples.

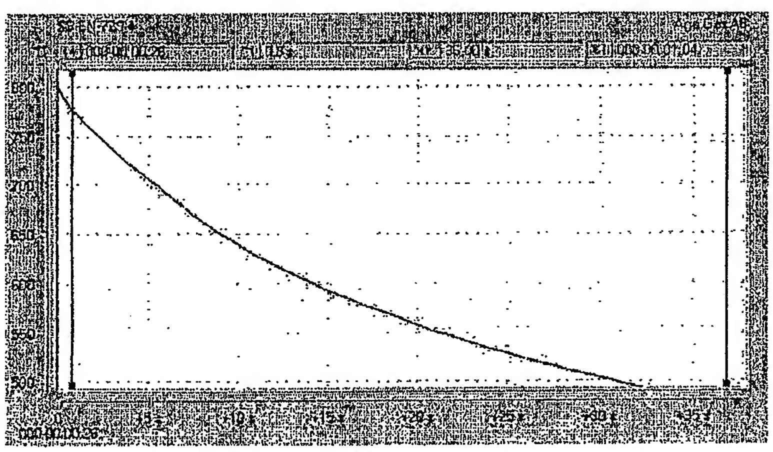


Fig. 2. Example of a recorded cooling curve.

The initial welding tests consist in joining 15 mm thick Ductile Iron plates (ferritic or pearlitic) to low carbon steel; the typical chemical compositions of the materials are listed in Table 3. As seen in Figure 3, the test coupon assembly had a gap of 2 to 3 mm, supported by a ceramic/copper backing, each plate having a bevel angle of 30°.

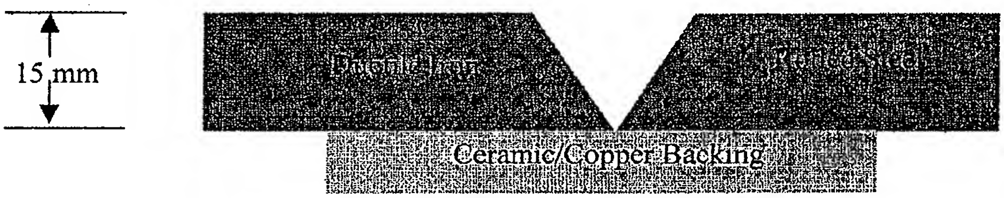


Fig. 3. Typical joint geometry.

Table 3. Typical Chemical Composition of Test Materials

Element, wt %	Ferritic Ductile Iron	Pearlitic Ductile Iron	Mild Steel
C	3.3 – 3.4	3.6 – 3.7	0.08
S	0.012	0.008	0.022
Si	2.40	2.4 – 2.5	0.24
P	0.017	0.010	0.015
Mn	0.16	0.15	0.5 – 0.6
Cr	0.027	0.03	0.12
Ni	0.025	0.06	0.08 – 0.13
Cu	0.058	0.70	0.19 – 0.25
Mg	0.035	0.025 – 0.035 *	-

* Vermicular graphite found in plates with lower magnesium content.

The welded specimens were characterized by metallographic examination, hardness and microhardness measurements and impact (-20 and + 20°C), tensile and bending tests. As shown in Figure 4, impact resistance was measured in different locations of the weldments as well as in the parent metals. Tensile properties were measured in both transverse and longitudinal directions vis-à-vis the weld, Figure 5.

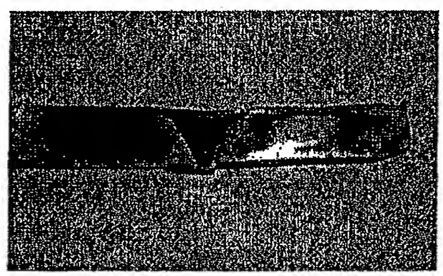


Fig. 4. Welded test coupon showing the locations for impact testing.

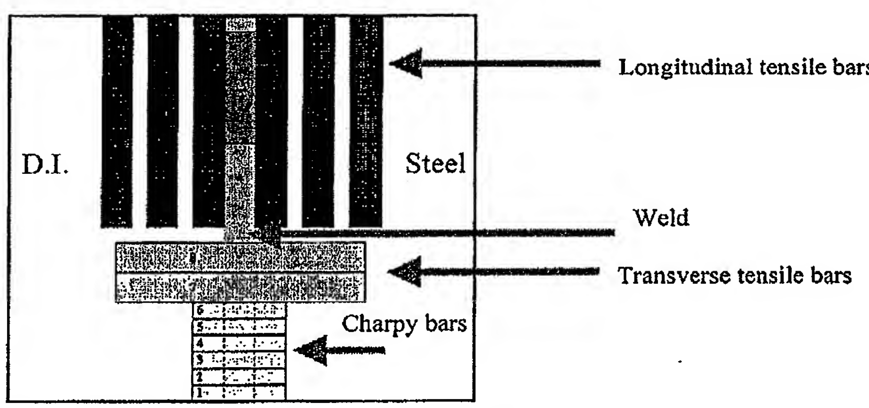
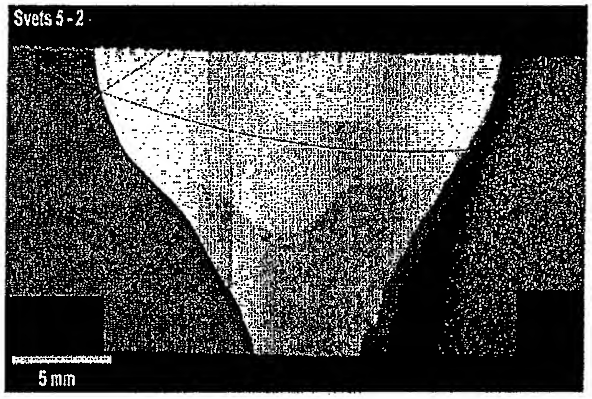


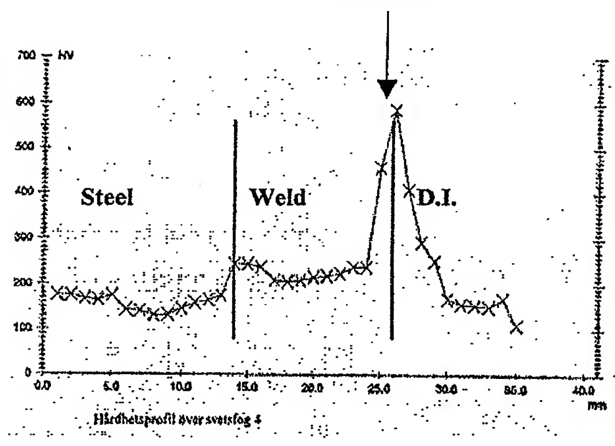
Fig. 5. Tensile and impact specimens positions in large plates.

FERRITIC DUCTILE IRONS

Figure 6 presents the typical macrostructure and microhardness profile of a welded steel-to-ferritic Ductile Iron joint obtained during the initial trials. Details of the microstructure of the weld are shown in Figure 7.



a)



b)

Fig. 6. Typical a) macrostructure and b) microhardness (VHN 1000g) profile obtained during the initial steel-to-ferritic ductile iron welding tests.

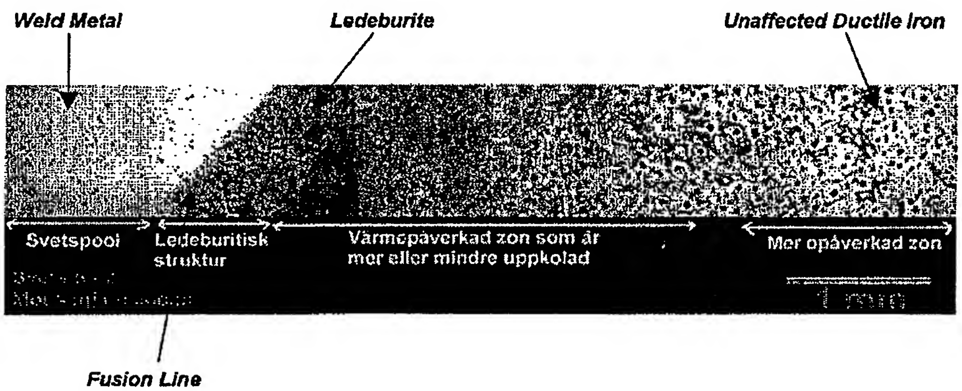


Fig. 7. Typical microstructure obtained during the initial steel-to-ferritic ductile iron welding tests.

The microhardness profile shows a smooth transition between the steel and the weld but a high hardness peak is noticed in the transition zone between the weld and the Ductile Iron. A narrow, typical fusion zone is observed at the steel – weld interface. When examining in more details the structure shown in Figure 6a, it is seen that a fusion zone, Figure 7, containing carbides, Figure 8, is present on the Ductile Iron side, resulting in high hardness in the vicinity of the fusion line. The adjacent Heat Affected Zone (HAZ) also displays a multi phase pearlite/ferrite/cementite structure, Figure 7. Such a mixed structure usually shows low impact resistance (< 5 J at room temperature) and tensile elongation (< 0.5 %). Following these initial tests, the objective of the project became to minimize the extent of the HAZ and fusion zone and to achieve properties approaching those of the parent Ductile Iron.

A. Ledeburite
B. Pearlite
C. Ferrite+Cementite+ Pearlite
D. Nodular Graphite
E. Weld

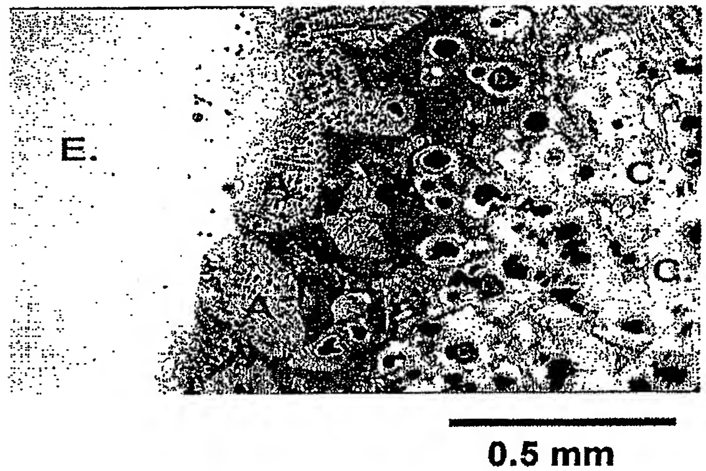
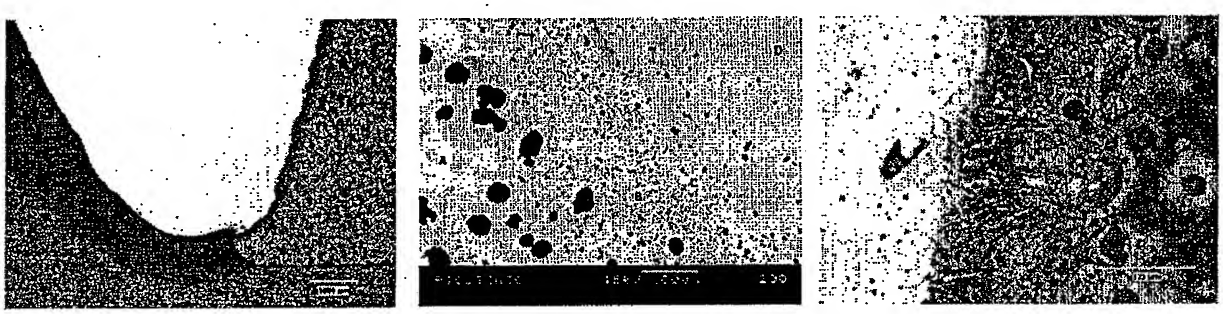


Fig. 8. Details of the weld – ductile iron junction zone.

As seen in Figure 9, changes in the welding procedures allowed to reduce the thickness of the embrittling layer to less than 0.3 mm. At higher magnification, Figures 9b and c, small graphite nodules are seen in the HAZ/fusion zone. Microhardness measurements (VHN 100g) in the HAZ/fusion zone ranges between 200-250 VHN, which is significantly lower than the 600 VHN peak shown in Figure 6b.



a) b) c)

Fig. 9. View of the ductile iron / weld interface
a) Low magnification (optical)
b) High magnification (SEM)
c) High magnification (optical)

The "improved" specimens were submitted to Charpy impact and bending tests. Table 4 presents the results of the impact tests; position number refers to those identified in Figure 4. It is seen that the range of the impact resistance values exceeds the data reported in the literature [3] for similar Ductile Iron and steel materials.

Table 4. Impact Test Results (+ 20° C)

Position	Test F1	Test F2	Test F3	Test F4	Reference (3)
Weld Metal (1) (J)	63 / 101	89 – 91	64 – 73	45	60
Fusion Zone (2) (J)	12 – 18	16 – 20	14 – 18	11 – 20	8, 11
HAZ (3) (J)	16 – 18	N.A.	14 – 16	-	11, 12
Ductile Iron (J)	12	12	12	14	-
Steel (J)	-	-	-	65	-
HAZ (Steel) (J)	-	-	-	50	-

Material used in Test F4 was also submitted to low temperature Charpy impact test. Results are presented in Table 5. It is seen that the parent Ductile Iron, its HAZ/fusion zone and the welding material have a ductile/brittle transition temperature lower than -20° C, while the steel HAZ is embrittled at low temperature.

Table 5. Effect of Test Temperature on Impact Resistance (Test F4)

Region	+ 20° C	- 20° C
Ductile Iron (J)	13.6	12.2
D.I. HAZ/Fusion zone (J)	13.2	11.3
Weld (J)	41.3	30.5
Steel HAZ (J)	50.2	19.0

Bending tests were carried out on welded specimens by hammering on the extremities of the Ductile Iron and steel sections in order to locate the maximum stress in the weld region. As seen in Figure 10, cracking occurred in the parent Ductile Iron, the weld remaining intact.

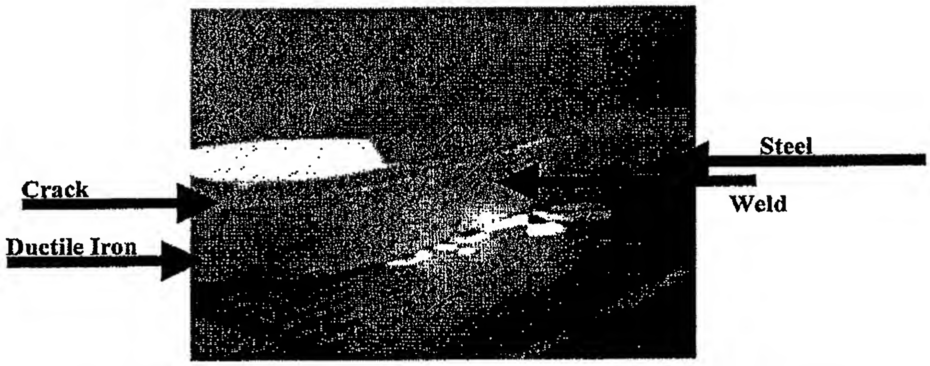
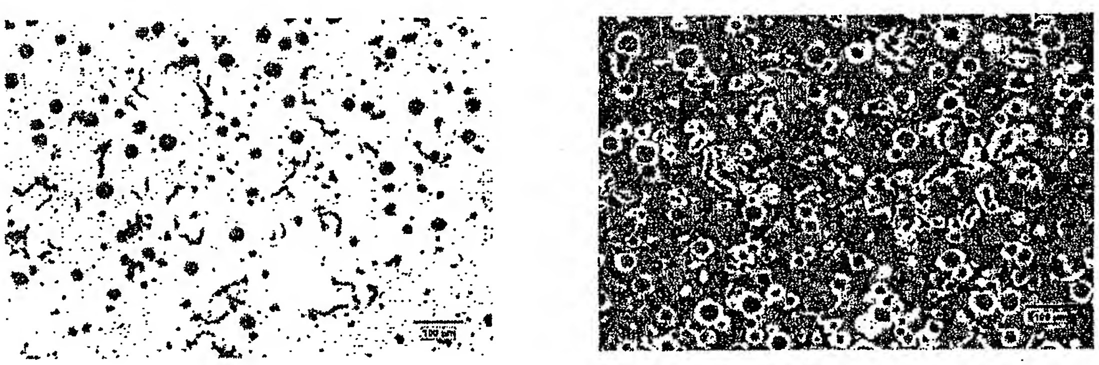


Fig. 10. Ferritic ductile iron – steel welded assembly after bending test.

PEARLITIC DUCTILE IRON

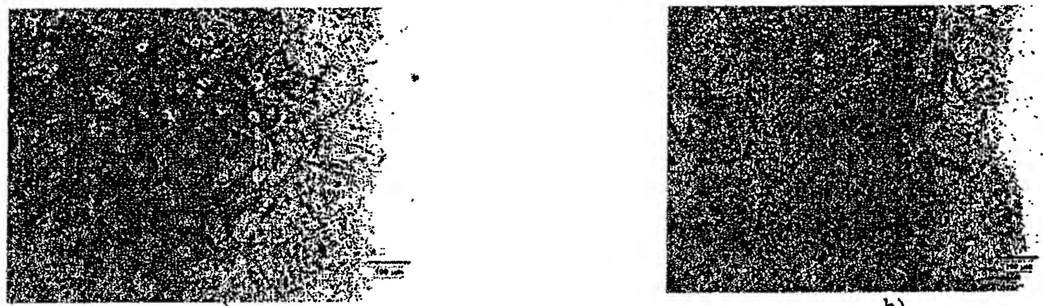
The conditions used for welding ferritic Ductile Iron were adapted to pearlitic irons. As indicated in Table 3, some of the pearlitic Ductile Iron plates were low in magnesium content, with a resulting structure consisting in a mixture of nodular and vermicular graphite particles in a pearlitic matrix, Figure 11. As a result, the typical tensile properties of these iron plates were those of a compacted graphite iron: UTS: 430-550 MPa, Elongation: 1-2%. Nevertheless, the properties measured in the HAZ and fusion zone should be comparable to those of welded pearlitic Ductile Irons since the vermicular graphite particles dissolved faster than the nodular ones during welding because of their large specific surface area.



a) b)

Fig. 11. Typical a) unetched and b) etched structures of the low Mg pearlitic ductile iron plates.

Examples of the typical fusion zone seen in the pearlitic Ductile Iron plates are presented in Figure 12. As for the ferritic irons, its thickness is in the 0.1 – 0.3 mm range. It is followed by a HAZ containing fine pearlite and tempered martensite.



a) b)

Fig. 12. Typical structure of HAZ/fusion zone in the pearlitic ductile iron plates.

As seen in Table 6, the typical microhardness measured in the HAZ/fusion zone was higher than that of the Ductile Iron, but did not reach values typical of a mostly carbidic structure (Figure 6b). As shown in Table 6, the hardness values of the HAZ/fusion zone reported in this study after annealing in the 600-650° C range are lower than those found in literature[3] for welds submitted to a similar heat treatment.

*Table 6. Microhardness (VHN 100g) of HAZ/Fusion Areas in Pearlitic Ductile Iron**

Test No.	Ductile Iron	HAZ/Fusion
P 1	314	322
P 2	300	322
P 3	268	297
P 4	323	366
P 5	277	336
Reference (3)	-	420 – 500

* Stress relieved at 600 – 650° C.

The properties of the welds (specimens P 6, P 7 and P 8) were verified by impact and tensile tests at room temperature. The location and identification of the specimens are shown in Figure 5.

Charpy V-notch impact energy was measured in the weld metal and the Ductile Iron HAZ/fusion zone. Results are presented in Table 7 and compared to those reported in literature [3]. It is worth noting that the welding rod used was Ni-61 in the referenced work, which most probably explained the difference seen in the properties of the weld metal zones. Also note that a high Mn welding rod was used for specimen P 8. The results obtained in the HAZ/fusion zone with the new welding procedures are clearly superior to those reported in the literature.

Table 7. Results of the Impact Tests – Pearlitic Ductile Iron

Notch Position	P 6	P 7	P 8*	Reference (3)
Weld (J)	24 – 38	16 – 27	12 – 16	11
HAZ/Fusion (J)	8 - 9	5 – 7	7	3 - 4

* High manganese welding rod.

A few tensile tests were carried out in the transverse direction of the weld. However, the results were strongly influenced by the tensile properties of the iron plates which were those of compacted graphite iron rather than those of Ductile Iron (lower ductility and strength); this makes them not representative of the mechanical strength of the weld. This is confirmed by the fact that some samples failed in the cast iron section of the bar, away from the weld.

As shown in Figure 5, tensile tests were run on longitudinal specimens including the following regions: the iron (no. 9); the HAZ (no. 10) and the fusion zone (no. 11). Results are presented in Table 8. As previously discussed, the poor nodularity of the graphite particles caused the samples machined in the iron to be the weakest. Those including the HAZ and fusion zone however exhibit tensile properties close to those of pearlitic Ductile Irons. In these samples, the vermicular graphite particles were dissolved rapidly (large specific surface) and graphite re-precipitated in a more regular shape.

Table 8. Tensile Properties of Longitudinal Specimens

Sample	P 6			P 7			P 8		
Position	9	10	11	9	10	11	9	10	11
Description	Iron	HAZ	Fusion	Iron	HAZ	Fusion	Iron	HAZ	Fusion
Yield St. (MPa)	344	358	363	444	450	450	442	453	447
UTS (MPa)	430	555	550	577	721	710	540	583	714
Elongation (%)	1.9	7.7	8.4	0.8	5.7	6.0	1.8	1.7	5.7

EXAMPLES OF WELDED ASSEMBLIES

Figure 13 shows several examples of geometries that were successfully welded. All shapes, i.e. plates, hollow shafts, ... can be assembled. Figure 14 presents another shaft assembly and details of the resulting weld.

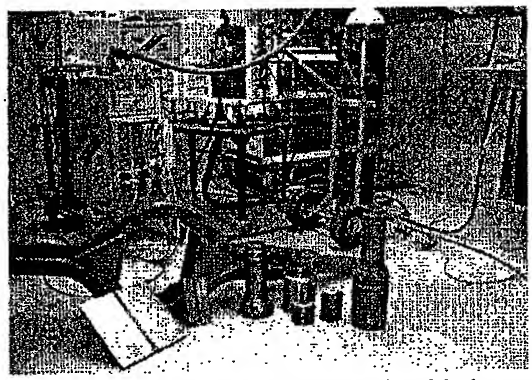
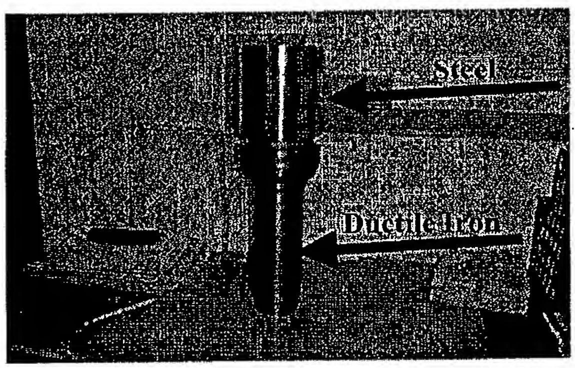
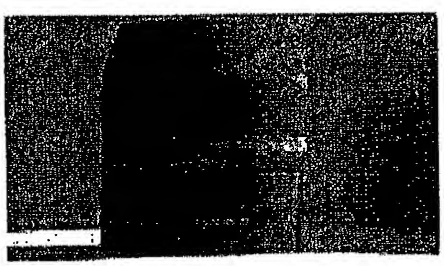


Fig. 13. Examples of ductile iron-to-steel welded assemblies.



a)



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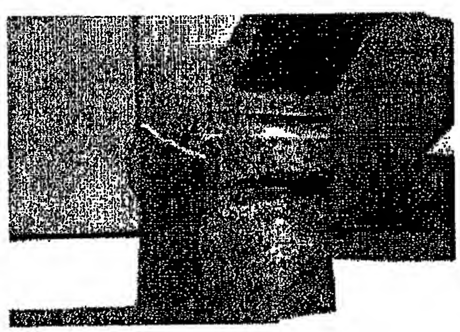
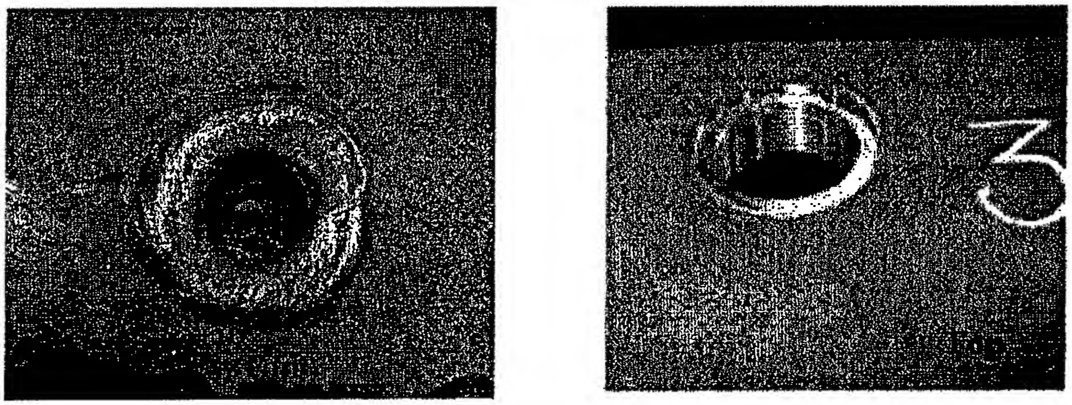


c)

Fig. 14. Details of a welded shaft assembly.

WELDING REPAIR TECHNIQUE

The welding parameters developed were used as basis for the development of a repair technique. In one case, a threaded hole was found defective in a Ductile Iron casting; the objective was to fill the hole with a material that could then be drilled and rethreaded. As seen in Figure 15, the hole can then be redrilled and rethreaded. After qualification tests, the repair technique was accepted by the manufacturer and implemented in the plant. Defects generated by the casting process could also be repaired.



a) b)

Fig. 15. ***a) Redrilled hole after welding repair.***
b) Rethreaded hole.

CONCLUSIONS

1. A welding process was developed to minimize the formation (extent) of a carbidic zone adjacent to the fusion line when welding Ductile Iron to steel.
2. The new procedures were found to reduce the thickness of the fusion zone from ~ 0.6 mm to < 0.3 mm.
3. The welding technique was found applicable to ferritic and pearlitic Ductile Irons.
4. The toughness and tensile properties of the resulting welds (for ferritic and pearlitic Ductile Irons) were significantly improved when compared to data reported in literature.
5. A repair technique for Ductile Iron castings was developed, based on criteria used for welding Ductile Iron to steel.

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November 21, 2006

Jorma Tani
Linde Gas
181-81
Lindigo, Sweden

Subject: AFS-"HOWARD F. TAYLOR AWARD"

Dear Mr. Tani:

It is a great pleasure to inform you and your colleagues that the Honorary Lectures and Papers Committee of the American Foundry Society has selected your paper #06-102 to receive the 2007 Howard F. Taylor Award.

The Howard F. Taylor Award was established to recognize a paper presented at the annual AFS Metalcasting Congress having the greatest long range technical significance to the cast metals industry. The award is intended to encourage technical excellence in an industry which requires the very best talents of its people by recognizing work which lifts the sights of our industry to the future and temporarily away from our day-to-day concerns.

Your paper, *"Welding Ductile Iron to Steel: A Reality* (#06-102), which was presented at the 110th Metalcasting Congress in Columbus, fulfills this criteria well and was selected for this honor from a field that includes all papers presented at the AFS Metalcasting Congresses during the past three years. The technology described in this paper significantly improves the properties in the heat affected zone when welding ductile iron castings to steel. This technology will allow ductile iron foundries and design engineers to develop new components that combine the versatility of casting with weldments and fabrications.

The Howard F. Taylor Award will be presented to you and your co-authors as part of the AFS Recognition Luncheon on Wednesday, May 16, 2007 at the 111th Metalcasting Congress in Houston, TX. We look forward to your presence at the award presentation. Please confirm your attendance at this prestigious event.

Sincerely,

STRobson

Stephen T. Robison
Senior Technical Director

cc: Ted Schom / Chair, Honorary Lectures & Papers Committee
John Grabel / Chair, AFS Cast Iron Division